

Experimental Characterization of 1-D Velocity Selection

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Abstract

We demonstrate a 1-D velocity selection technique which relies on combining magnetic and optical potentials. We have selected atom clouds with temperatures as low as 2.9% of the initial temperature, with an efficiency of 1%. The efficiency (percentage of atoms selected) of the technique can vary as slowly as the square root of the final temperature. In addition to selecting the coldest atoms from a cloud, this technique imparts a sharp cut-off in the velocity distribution. The cold selected atoms are confined in a small well, spatially separated from higher energy atoms. Such a non-thermal distribution may be useful for atom optics experiments, such as studies of atom tunneling.

I. INTRODUCTION

The field of atom optics has experienced a period of dramatic growth recently, largely due to the success of experiments on Bose-Einstein Condensation (BEC). The achievement of BEC itself was based largely on the success of evaporative cooling[1, 2]. Unfortunately, evaporative cooling is usually accomplished with a very high cost in atom number, such that the typical efficiency (percentage of atoms remaining of the initial sample) varies linearly with temperature[3]. While this method works very well, it is quite lossy compared to certain other techniques, particularly if one is concerned with temperatures along only one dimension. Other cooling techniques have been shown to be useful for achieving high phase-space density, such as Raman Sideband Cooling[4, 5]. This technique relies on deep potential wells, which imply a large zero-point energy, typically resulting in temperatures on the order of the recoil temperature after adiabatic release. To cool below the recoil limit (in 1-D) methods such as Raman cooling [6, 7] and VSCPT[8] have proven useful in getting cold atoms, but again they prove inefficient in atom number.

In this paper we describe a technique to select the coldest atoms in one dimension to obtain long deBroglie wavelengths which could be used to study atom-optical effects such as tunneling[9], quantum potential scattering[10] and chaos[11, 12, 13]. This technique can be implemented after the earlier listed techniques as it has no fundamental limit. The process of velocity selection can also be quite efficient, the efficiency of the selection dropping only as the square root of the ratio of the final to initial temperature. This selection process confines the atoms in a single potential well and imparts a sharp cut-off in velocity, yielding a non-thermal distribution. The sharp cut-off in energy guarantees that there are no high energy atoms in the system, making it useful for studying effects sensitive to energy, such as tunneling and collisions.

II. THEORY

We begin by considering a dilute cloud of laser-cooled atoms where the density is low enough that collisions and rethermalization may be neglected. Selection of low energy atoms is accomplished by sudden turn on of a potential that has a local minimum. The potential is comprised of a potential gradient and a barrier arranged to create a local minimum in

the region of the atom cloud as shown in Figure 1. In the classical limit any atom that begins in the potential well and has sufficiently low kinetic energy will become trapped in the well. Higher energy atoms will simply pass over the barrier and accelerate along the potential gradient, quickly becoming spatially separated from the trapped atoms.

We first consider the limit where the potential energy difference across the cloud due to the gradient ($\approx 2U'r$, where r is the rms radius of the cloud) is negligible compared to the kinetic energy ($k_B T/2$ at an initial temperature T). Since the initial distribution of laser-cooled atoms is essentially thermal, the final velocity distribution is a truncated Gaussian, keeping the low-velocity atoms and discarding the high-energy atoms. The efficiency of the selection process is then $\eta = \frac{1}{\sqrt{2\pi}\sigma} \int_{-v_m}^{v_m} e^{-v^2/2\sigma^2} dv$ where σ is the rms velocity of the cloud and v_m is the maximum velocity a selected atom can have. The Gaussian distribution is relatively flat for $v_m \ll \sigma$, allowing the efficiency to be approximated as $\eta \simeq \sqrt{\frac{2}{\pi}} \frac{v_m}{\sigma} = \sqrt{\frac{4U_0}{\pi k_B T}}$. The selected cloud now has an essentially square velocity distribution, with a mean kinetic energy of $U_0/3$. If we define this mean kinetic energy as a pseudo-temperature $k_B T_s/2$, then the efficiency of selection is $\eta = \sqrt{\frac{6T_s}{\pi T}}$. This allows one to reduce the mean (1D) kinetic energy by a factor of 200 while still retaining 10% of the atoms. In comparison, the efficiency of evaporative cooling depends linearly on the temperature ratio[3], implying that about 0.5% of the atoms would remain after cooling by a factor of 200.

In the case of a high gradient, the atoms begin with a significant amount of potential energy as compared to the height of the barrier. Since atoms farther away from the barrier gain more kinetic energy than closer atoms, there is a limit to the distance an atom can be from the barrier and still be selected. The maximum distance an atom may be from the well and still be trapped is then $z_m = U_0/U'$. A large gradient will make the distance x_m smaller than the size of the cloud. The most efficient selection will then occur when the potential barrier is placed in the center of the atom cloud. For z_m and v_m smaller than the rms spatial and velocity distributions, the mean kinetic energy $k_B T_{s/2}$ works out to be $U_0/4$. The efficiency varies as $\left(\frac{T_s}{T}\right)^{3/2}$ where a factor $T_s^{1/2}$ comes from the velocity distribution and a factor of T_s from the gradient[14]. The 3/2 power leads to a large decrease in the selection efficiency, making large potential gradients undesirable.

Due to experimental constraints, the potential gradient cannot be made arbitrarily small. In order to obtain the spatial separation of the hot and selected clouds within a reasonable time, a minimum gradient is required to ensure that the atom cloud propagates further than

it expands. When very cold atoms are desired one must always use very small barriers, in which case the potential energy across the cloud will be greater than the height of the barrier. For these small barriers heights, one will have a resulting efficiency that varies as $T_s^{3/2}$.

In both limits of the selection process, the atoms have a maximum energy defined by the barrier. No atom with energy greater than U_0 can remain within the well created by the potential barrier and gradient. The sharp cut-off in velocity (energy) can be observed in the long-time free expansion of the cloud as a lack of the long tails, or it can be observed directly by performing a deconvolution of the final spatial distribution. For the limit of very low potential energy the velocity distribution will approach a truncated Gaussian. For large gradients the velocity distribution appears more triangular than square. Detailed simulations of this technique are to be published separately[14]. Quantum effects (preparation of single bound states) have also been predicted, but for the regime of the present experiment, the classical approximation is accurate.

III. EXPERIMENT

We begin with a cloud of ^{85}Rb atoms cooled in a $\sigma^+\sigma^-$ molasses to a temperature on the order of $10\mu\text{K}$. The cloud has an rms radius r of about 500 microns for this experiment. Immediately following a cooling stage, we optically pump the atoms to the doubly polarized $|F=3, m_F=3\rangle$ state to ensure that all the atoms experience the same potential. A weak magnetic quadrupole trap consisting of a pair of anti-Helmholtz coils is turned on in conjunction with a pair of bias coils along the same axis as the quadrupole coils to create potential gradients of 10 G/cm or less. The bias coils are in a Helmholtz configuration and create a constant magnetic field in the region of the atoms. This bias field serves to displace the center of the quadrupole field by a distance $z_0 = B_b/B'$ where B_b is the strength of the bias field, and B' is the gradient of the quadrupole field along the z direction. The magnitude of the bias field is always chosen such that the trap center is displaced by a distance greater than the size of the cloud. An optical dipole potential is turned on at the same instant as the magnetic fields. The dipole barrier consists of a Ti:Sapphire laser operating 210 GHz to the blue of the Rubidium D2 resonance. The beam is focused to a vertical line 12 microns wide and 6 mm tall that intersects the cloud of atoms. The intensity of the

beam is controlled with an acousto-optic modulator, enabling us to vary the potential height of the barrier from $100\mu K$ down to the nanoKelvin range. The ratio between the potential and kinetic energy is controlled by varying the temperature and size of the initial cloud, and varying the strength of the gradient. To study a larger range of parameters the trapped atoms are sometimes compressed prior to the experiment, heating the cloud to about $26\mu K$ while reducing its size to $160\mu m$.

When the displaced quadrupole field is turned on, the atoms are located far from the $z = 0$ origin of the magnetic trap and instead of experiencing a conical potential (which would couple different spatial degrees of freedom) they see the potential locally as a (parabolic) conic section along x and y . The atoms therefore experience a potential that is essentially separable: harmonic along the x and y axes, and linear along z . This helps to prevent mixing between the different degrees of freedom, justifying the treatment of this as a 1-D problem and the possibility of achieving $T_z \ll T_x, T_y$. The combination of the magnetic potential and the dipole potential creates a well in which atoms may be trapped. The atoms begin accelerating along the z axis toward the center of the trap. Any atom which starts off on the far side of the barrier relative to the trap center can be trapped if the atom has sufficiently low energy. The well depth U_0 is smaller than the barrier height by a correction term on the order of $U'\sigma_L$ where U' is the gradient of the magnetic field and σ_L is the $1/e^2$ radius of the laser beam. For large barrier heights this effect is negligible.

The atom cloud is allowed to evolve within the potential long enough for several oscillations to occur. For typical parameters used the well is $120\mu m$ wide, with the selected atoms having an rms velocity of 1 cm/s allowing for almost 3 full oscillations within 20 milliseconds. After this time, both the magnetic and optical fields are turned off to determine the temperature by a time of flight measurement. The mean energy of the cloud is determined by fitting the clouds to a 1-D Boltzmann distribution. The efficiency of the selection (fraction of atoms selected) is determined by measuring the ratio of selected to non-selected atoms 0.5 milliseconds after the gradient and barrier are turned off. A sample image of the total cloud distribution (selected and non-selected) is shown in Figure 2, after 20 ms of free expansion, long enough for significant separation of the selected and non-selected components. The different regimes for the initial cloud are achieved by varying the trapping procedure and MOT parameters. The large potential energy regime is achieved by using a large (400 micron) cloud of atoms cooled to about $26\mu K$ placed into a relatively high gradi-

ent of 8 G/cm, resulting in the potential energy across the cloud varying by $42 \mu K$. The low potential energy regime is achieved by compressing the MOT before beginning selection. In this case the initial clouds are 160 microns across with a temperatures near $25 \mu K$ and are subsequently placed into traps with gradients of 3 G/cm, with the potential energy varying across the cloud by $6 \mu K$. Figure 3 shows the temperature of the selected cloud versus the potential height of the barrier. The initial conditions of the clouds are characterized by a parameter $\beta = 2U'r/k_B T$, which is the ratio of the potential energy difference across the cloud to the kinetic energy at the start of the selection. The temperature of the selected clouds is plotted versus the height of the potential barrier for two sets of data with $\beta = 0.23$ and 1.7 for the solid and hollow circles respectively. For the four lowest barrier height data points for each set, the slopes are 0.34 and 0.40 respectively, in rough agreement with the prediction of $k_B T_s = U/3$. The lowest cooling ratio T_s/T we observed was 1/35, with the lowest temperature observed being 750 nK. The observed temperature is higher than the theoretical prediction of a 1-D classical simulation that includes only the initial cloud parameters, the barrier height and the gradient[14]. The experimental temperatures may be higher than theory due to residual mixing of the spatial degrees of freedom, heating by scattering photons from the dipole barrier or leakage of atoms around the barrier.

The efficiency of the selection process is determined by measuring the ratio of selected atoms to the total number of atoms 0.5 milliseconds after the selection process is completed. In Figure 4, we see the efficiency for different barrier heights with the corresponding theoretical curves. The initial cloud in each case started at a temperature of $26 \mu K$ but with two values of β as before: 0.23 and 1.72, corresponding to the circles and squares respectively. For $\beta = 0.23$ (circles), the near square root dependence of efficiency on well depth (U_o) is visible. For the higher ratio $\beta = 1.7$, a more linear dependence is observed. The experimental efficiency is found to be somewhat lower than the theoretical expectation. Even in the case of weak gradients, a $3/2$ power law dependence will be observed for extremely low barrier heights, since the barrier potential will then be lower than the potential energy across the cloud.

IV. CONCLUSION

In conclusion, we have demonstrated a new technique to obtain cold atoms in one dimension. We have cooled to temperatures as low as $1/35$ th of the initial temperature of 26 μK , reaching 750 nK with an efficiency of 1%. This technique is not limited by the recoil temperature and in fact has no fundamental limit. This method can be more efficient than other techniques such as evaporative cooling, since the efficiency can vary as the square root of the ratio of the final to initial temperature. The cold selected atoms are confined in a single one-dimensional well, spatially separated from the higher energy atoms. This technique does not produce a thermal distribution of atoms, but instead imposes a sharp cut in the velocity distribution, making it useful for studying effects that are sensitive to energy such as tunneling, chaos and quantum-potential scattering[10, 11, 12].

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Fig 1. Principle of velocity selection. a) Atoms in free-space immediately after release from the trap. b) Potentials turned on. Atoms begin accelerating downhill. c) End of selection. Cold atoms trapped in small well while hot atoms are travelling away from the well.

Fig 2. Sample data image of velocity selection to demonstrate spatial separation of selected atoms from hotter atoms. A large potential gradient was used to show the separation before significant expansion occurred.

Fig 3. Plot of experimental data showing temperature versus well depth. The solid circles and hollow diamonds refer to weak ($\beta = 0.23$) and strong ($\beta = 1.7$) potential gradients respectively. The solid and dashed lines are theoretical curves for the weak and strong gradients respectively. The theoretical curves are obtained from simulation with no free parameters. Both experimental data sets have slopes with a temperature of about $1/4$ of the height of the barrier. The lowest temperature achieved was 750 nK.

Fig 4. Efficiency vs the well depth is shown. The solid circles and hollow squares refer to weak ($\beta = 0.23$) and strong ($\beta = 1.7$) potential gradients respectively. The solid and dashed lines are theoretical curves with no free parameters.